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Time Domain Reflectometry for damage detection of laminated CFRP plate

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Abstract

Recently, high toughness Carbon Fiber Reinforced Polymer (CFRP) laminates are used to primary structures. The tough CFRP yields small fiber breakages when delamination crack is made in many cases. This requires a detection system of fiber breakages at low cost for large laminated CFRP structures. In the previous study, Time Domain Reflectometry (TDR) method is adopted for the detection of the fiber breakages of the CFRP plate. In the present study, damage detection in the transverse direction is performed using the array of electrodes. The method is applied to a CFRP strip specimen of 2 m length with a notch. As a result, all electrodes detected the small notch. This means the electrode array did not detect the location of the damage in the transverse direction. Computer simulation was performed to confirm the pulse wave propagation in the transverse direction using Finite Difference Time Domain (FDTD) method. The FDTD successfully showed the pulse signal propagation in the transverse direction. Future work is indispensable to develop a new technology to detect the location of the damage in the transverse direction.

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14. ABSTRACT

Recently, high toughness Carbon Fiber Reinforced Polymer (CFRP) laminates are used to primary structures. The tough CFRP yields small fiber breakages when delamination crack is made in many cases. This requires a detection system of fiber breakages at low cost for large laminated CFRP structures. In the previous study, Time Domain Reflectometry (TDR) method is adopted for the detection of the fiber breakages of the CFRP plate. In the present study, damage detection in the transverse direction is performed using the array of electrodes. The method is applied to a CFRP strip specimen of 2 m length with a notch. As a result, all electrodes detected the small notch. This means the electrode array did not detect the location of the damage in the transverse direction. Computer simulation was performed to confirm the pulse wave propagation in the transverse direction using Finite Difference Time Domain (FDTD) method. The FDTD successfully showed the pulse signal propagation in the transverse direction. Future work is indispensable to develop a new technology to detect the location of the damage in the transverse direction.

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1. **Introduction**

Carbon Fiber Reinforced Polymer (CFRP) laminates are applied to many aerospace structures. The laminated CFRP structures are very effective in weight saving in aeronautical structural components. For these laminated CFRP structures, it is, however, difficult to detect damage such as delamination, matrix cracks, and local fiber breakages because these damages are difficult to detect for visual inspection from the outside of the structure. This difficulty of inspection of the laminated CFRP structures demands the development of automatic monitoring or damage detection systems.

Carbon fibers are adopted as reinforcements in CFRP, and the carbon fibers are excellent electric conductors at the same time. The carbon fiber has been used as a strain sensor for decades [1]. Applied strain monitoring of the CFRP structures is very important to confirm integrity of processing. Vibration and applied stress monitoring are also used to determine the effect of external load. Recently, electrical resistance change measurement has been employed to detect and/or monitor internal damage to CFRP laminates by many researchers [2-10]. Electrical resistance change measurement does not require expensive instruments. Since the method adopts the carbon fiber itself as a sensor, it does not cause a reduction in strength, and can be applied to existing CFRP structures. Further, measurement requires no additional research to fabricate composite structures, as it does not require embedded sensors.

Although electrical resistance change measurement has advantages over other methods of structural health monitoring, it has received little attention until recent years. This is because the strong anisotropic electrical resistance of CFRP causes complicated behavior in electrical resistance change when it is measured by conventional methods. Recent research has shed light on many of the problems in this area and enabled identification of damage location and dimension by measurement of electrical resistance change at multiple points within target CFRP structures [11-18].

The electrical resistance change method (ERCM), however, requires a lot of electrodes on the target CFRP structures to measure electrical resistance change at multiple segments of the CFRP structure although the ERCM provides highly precise estimation results. These electrodes are made using an electrical copper plating method. Although the portable type machines have already commercially available, to make a lot of electrodes on the target CFRP structure is tiresome.

In the previous study, Time Domain Reflectometry (TDR) method is applied to a unidirectional laminated CFRP structure for the first time. Several methods to make an electrode were tried and copper plating at the end of the CFRP structure is adopted in the previous study. As the time difference between the input pulse and the reflected pulse is small, pulse compression technique is found to be useless for the dimension of the actual CFRP structures. As the attenuation of the input pulse is large because of the high electrical resistance of CFRP compared with copper wire, four meters of the pulse transmission length is the maximum to detect the reflected pulse. The previous research successfully detected carbon-fiber breakages that are made by drill holes.

The present study continues research on the application of the TDR method for the CFRP laminates. On the basis of the results of the previous study, the present research focuses on the application of the TDR method to investigate the effect of the CFRP plate width. Small electrodes are made at the end of the CFRP specimen, and the pulse wave propagation in the transverse direction is investigated experimentally. In addition, Finite Difference Time Domain (FDTD) method is applied to solve the Maxwell's equation to know the pulse wave propagation.

2. Time domain reflectometry method

Time domain reflectometry (TDR) method uses an electrical pulse wave and observes the reflected waveform. This method is actually used in order to detect the location of damages in the transmission lines, such as the computer network cable. Using a pulse wave generator and a digital oscilloscope as shown in Fig. 1, reflected wave or transmitted wave of the cable can be analyzed and the location of the disconnection or damage of the cable can be detected. The distance to the damage from the input terminal can be calculated using the equation as follows.

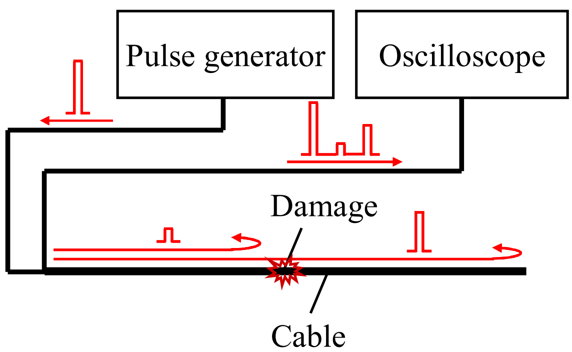

Fig. 1 Schematic representation of TDR method.

$$L = \frac{V_p \Delta T}{2} \tag{1}$$

where L is the distance, ΔT is the time difference between the input pulse and the reflected pulse, and V_p is transmitted velocity of the electrical pulse. CFRP has high electric conductivity. This enables us to use TDR method for CFRP. A pulse signal transmits in fiber direction and is reflected at the end. When fiber damages occur, the pulse signal is reflected from the damaged fibers. The reflected pulse signal from the damage is observed earlier than the reflected pulse signal from the end of the fiber. Observation of the time interval of the reflected pulse signal enables us to know the location of the damages in the CFRP structures.

3. Experiments

TDR method is applied to a CFRP strip specimen of 2 m length. A notch is made to simulate fiber breakages and the notch is detected from the time difference of reflected pulse signal.

3.1 Material CFRP laminates are fabricated from unidirectional carbon fiber/epoxy prepreg sheets PYLOFIL#380 (Mitsubishi Rayon Co., Ltd). Curing conditions are 130×°C× 90 min under vacuum pressure. Since the specimen length is very long, two film heaters of 1 m length are cure the specimens. The stacking sequence of CFRP is unidirectional of $[0_4]_T$. Specimens are 1980 mm long and 120 mm wide. To cure the specimen, only half of the specimen is cured. The rest of the specimen is left as prepreg. Before the experimental tests, we have checked that there was no significant difference in the electrical pulse wave velocity between in the prepreg and in the cured CFRP.

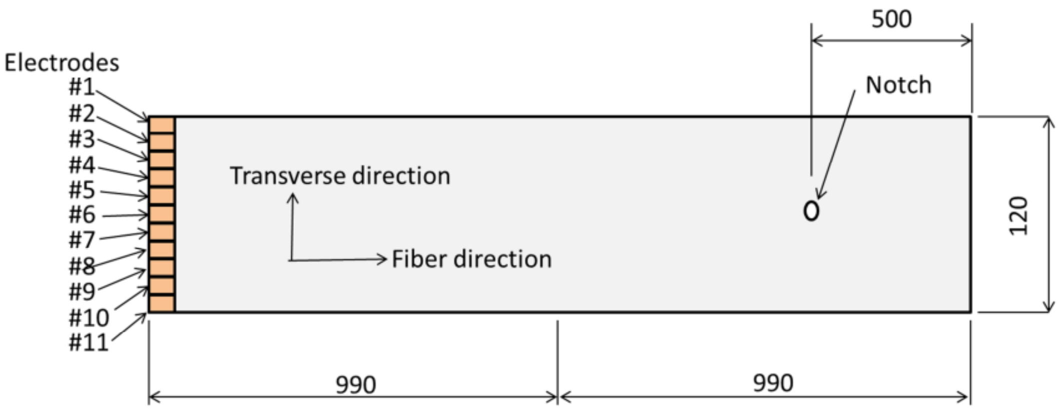

Fig.2 Specimen configuration

The input terminal requires reliable and low contact resistance electrodes. In order to make the reliable electrodes, electrical copper plating method as shown in Fig. 2 is applied here. The copper plating electrodes are confirmed to be very small contact resistance and it does not depend on the worker's skill.

3.2 Experimental method Figure 3 shows the experimental setup used here. A function generator of Tektronix AFG3251 (pulse amplitude is 5 v and pulse width is 4 ns) is used as a pulse generator and a Tektronix TDS5034 digital oscilloscope (sampling time is 0.01 ns) is used as a data-storage machine to observe reflected pulse signal. A directional coupler is used to remove the pulse wave from the generator here. A transmission line consists of the signal line and the ground line. An aluminum plate is used as the ground plane here. Instead, we can use copper mesh layer, which is usually applied as an anti-lighting damage system, as a ground in an actual aircraft wing. The aluminum plate enables us to get significantly favorite impedance matching between CFRP and coaxial cable. Notch length types used here is 42 mm. The notch is made at the location of 500 mm from the right end of the CFRP specimen as shown in Fig. 2.

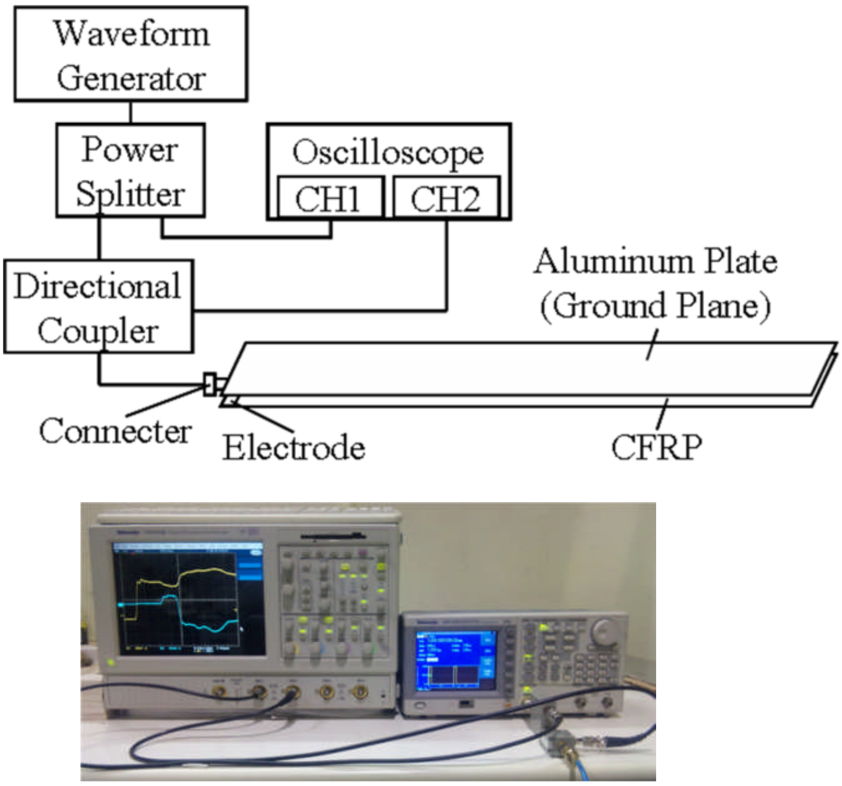

Fig.3 Experimental setup

In the present study, eleven separated electrodes are made at the end of the specimen as shown in Fig.2. To make these electrodes, at first one electrode was made by using copper plating method as shown in Fig.4. The specimen end is shown in Fig.5

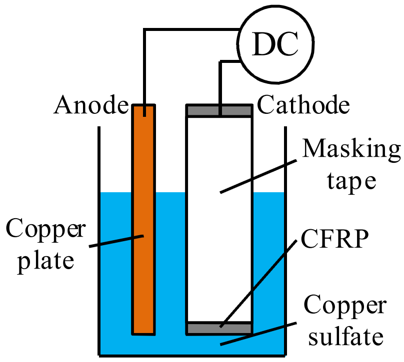

Fig.4 Copper plating method

Fig. 5 Electrode made by the copper plating

After making the copper plating electrode at the end of the specimen, the electrode was separated into 11 electrodes as shown in Fig.2 using a normal knife. Since this end is not cured, it was quite easy to cut the end into 11 electrodes with a knife.

4. **Experimental results and discussion**

The results obtained are shown in Fig. 6. The ordinate is the difference of the measured electric voltage from the result obtained with the intact specimen. The abscissa is the time. The results show that all results show the identical reflected signals.

Since the CFRP is unidirectional, the CFRP plate has strongly orthotropic electric conductance. The reflected pulse signals were expected to be different with each other because of the strongly orthotropic electric conductance. Figure 7 shows the expected pulse signal reflection. When a pulse signal is applied to the electrode number 2, the pulse signal was expected to propagate straight as shown like a blue arrow. When a pulse signal is applied to the center electrode #6, the pulse signal is expected to propagate in the center like an orange arrow. Because of the strongly orthotropic electric conductance, the pulse signal is expected not to propagate in the transverse direction. However, the experimental results show the pulse signal propagates even in the transverse direction. This result requires the additional computer simulation to understand the actual pulse signal propagation in the CFRP plate.

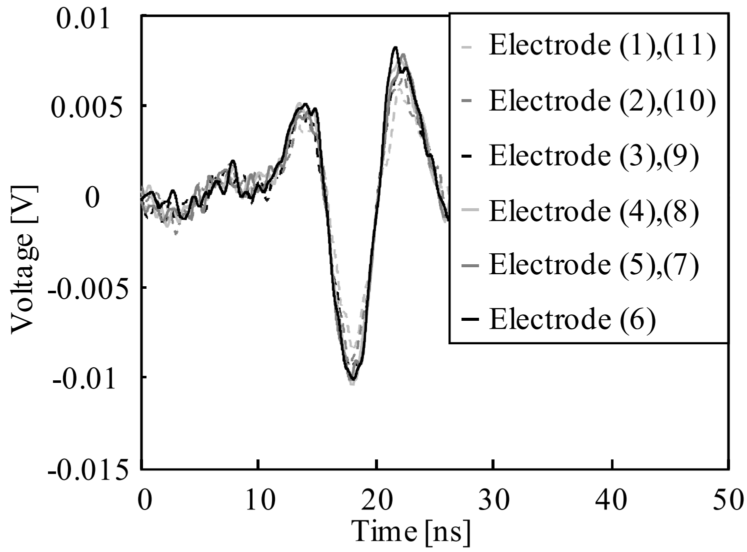

Fig.6 Reflected pulse signal from all electrodes

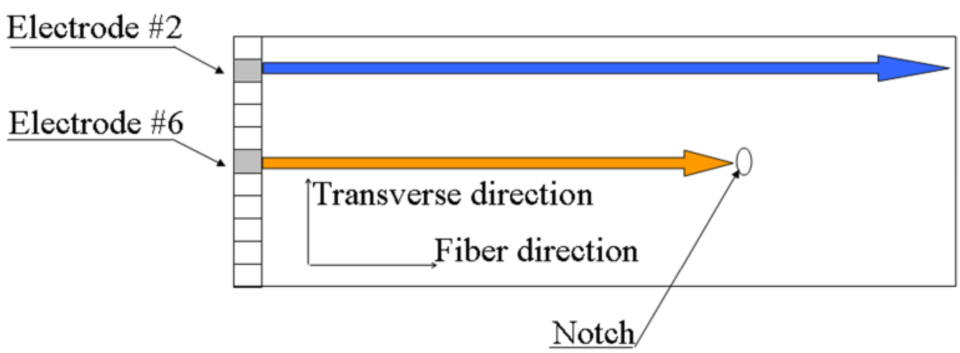

Fig.7 Expected pulse signal propagation

5. **Computer simulation analysis**

5.1 Finite difference time domain method Analysis using finite difference time domain (FDTD) method is conducted here. This method is a computational electrodynamics modeling technique and solves Maxwell's equations in the time domain. A source of the wave, geometric objects and absorbing boundary condition are prepared as input data, and the target field is evolved in time following preset discrete time steps. The FDTD simulation enables us to know how the electric pulse wave propagates in the CFRP specimen.

5.2 Analytical method The parallel plate model comprising of a CFRP strip specimen of 2 m length and an aluminum plate were simulated by the FDTD simulation free software Meep. Figure 8 shows the model for FDTD method. Properties of IM600/133 are used as properties of CFRP. Table 1 shows the electrical conductivity of IM600/133. In order to prevent the electromagnetic wave from reflecting from the boundary, perfectly matched layers (PML) is used as the absorbing boundary layers. The current source is applied at input terminal. The current source is the Gaussian pulse as shown here.

$$J = A\exp\left(-i\omega t - (t-t_0)^2 / 2w^2\right) \tag{2}$$

where A=1, w=5, ω=0.01. The notch length types used here are 18 and 30 [mm]. Detail condition of the calculation is shown in appendix.

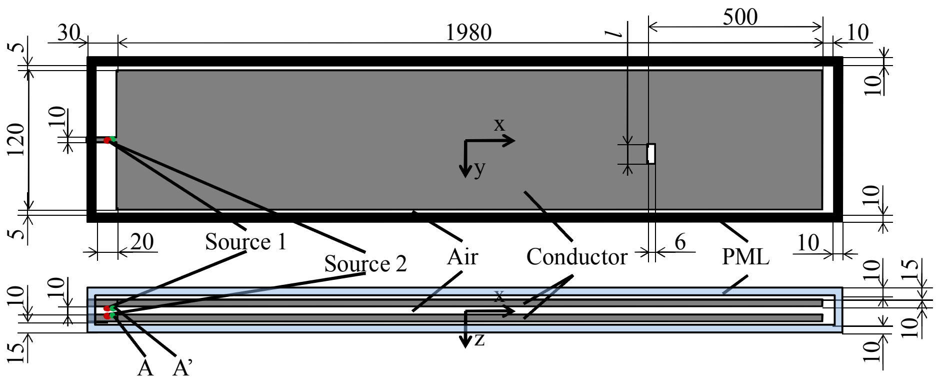

Fig. 8 Parallel plate model for FDTD method.

Table 1 Electrical conductivity of IM600/133 [/(Ω・m)]

Longitudinal	Transverse	Thickness
3.60×10^4	1.15	1.79×10^{-3}

5.3 Results The results obtained are shown in Fig. 9, Fig. 10 and Fig. 11. The results show E_z of z=0 plane at 0.8, 3.0, 6.5 and 10.0 [ns]. The pulse signal is reflected at the end of the specimen. When a notch locates in the CFRP plate, the pulse signal is also reflected at the damage as shown here. The propagation of the pulse in the transverse direction is clearly observed here. This indicates the pulse wave easily propagates in the transverse direction even though the electric conductance in the transverse direction is very small. Additionally, the results show that the larger reflected wave exits when the notch length is larger. Figure 12 shows the TDR waveforms calculated from the analysis results. The peak time of the reflected pulse waves coincide with the experimental result. This shows that analysis using FDTD method almost exactly simulate the experimental TDR method. This shows that we can know the pulse wave propagation using the simulation results. The FDTD method may enable us to develop a new technology that detects location in the transverse direction. This is future work.

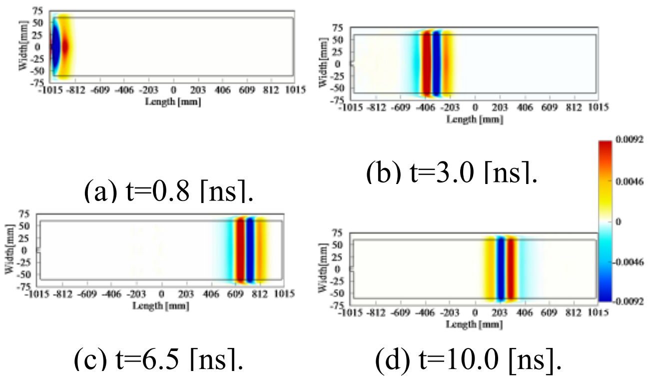

Fig. 9 Analysis E_z of z=0 plane (No notch).

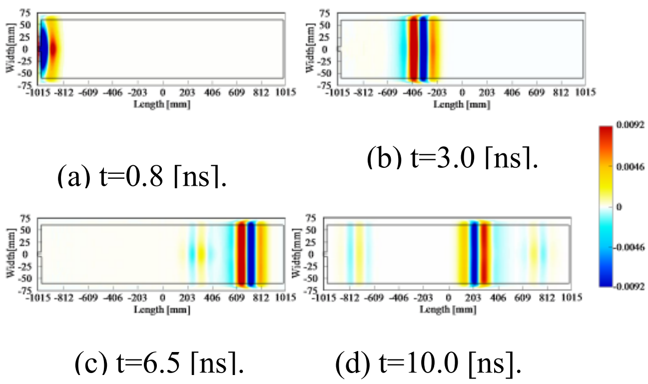

Fig. 11 Analysis E_z of z=0 plane (l=30 [mm]).

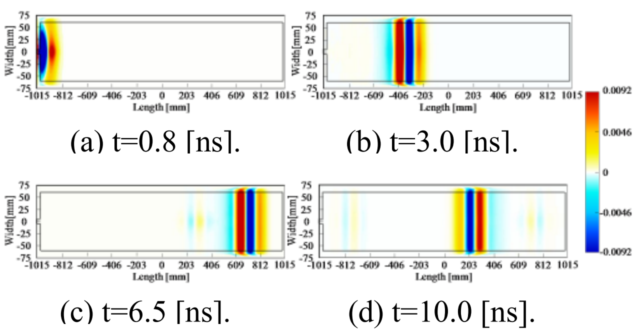

Fig. 10 Analysis E_z of z=0 plane (l=18 [mm]).

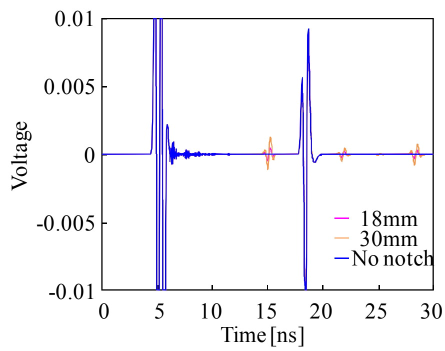

Fig. 12 TDR waveforms from analysis.

5. Conclusions

The present study shows the availability of time domain reflectometry (TDR) for damage detection of CFRP. TDR method is applied to a 2 m unidirectional CFRP strip specimen. Fiber damages are modeled as a notch and the notch is detected from the reflected waveform. The propagation of the pulse wave in the CFRP specimen is investigated by the simulation using FDTD method. The analysis results are compared with experimental results. The results obtained are follows.

(1) The electrode array cannot distinguish the location of the damage in the transverse direction.
(2) Pulse signal transmission of a CFRP plate can be calculated using FDTD method.
(3) The propagation of the pulse signal in the transverse direction is confirmed using the FDTD method.

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Appendix

Figure A1 shows the input pulse signal. The ordinate is the voltage and the abscissa is the time. As shown in Fig.A1, the frequency of the pulse signal is approximately 700 M Hz. With the speed of light, the wave length of the signal can be calculated. The calculated wave length is approximately 400 mm.

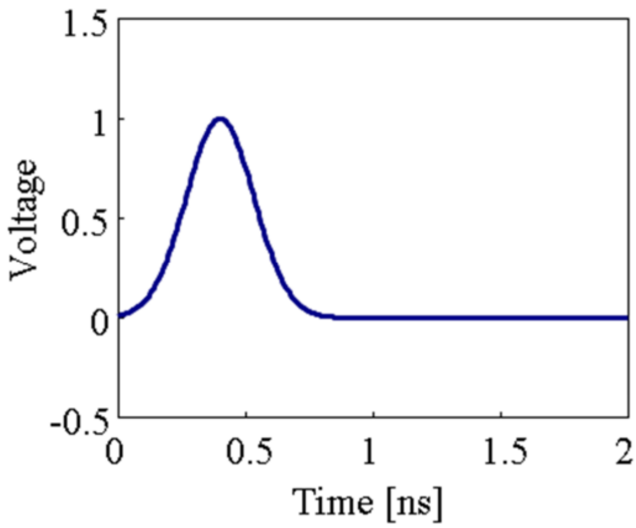

Fig. A1 Input pulse signal

The wave length of 400 [mm] is large enough when compared with the characteristic length of normal CFRP: characteristic length of CFRP is approximately 10 [μm]. This means we can deal with the CFRP as orthotropic conductive materials without any capacitance and inductance for this frequency as shown in Fig. A2.

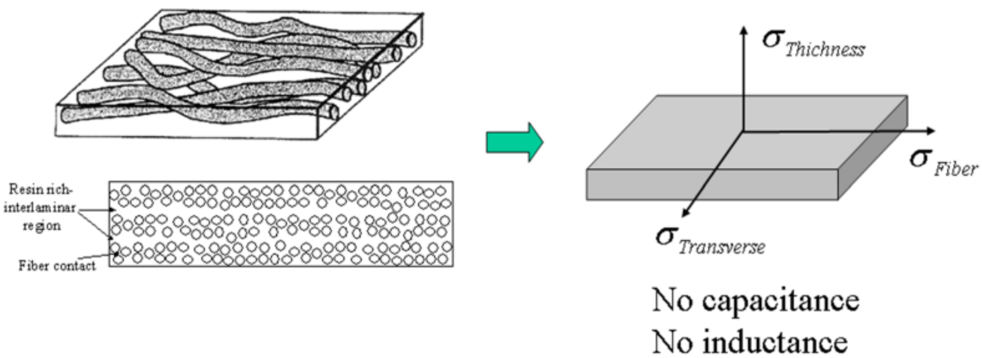

Fig. A2 Orthotropic conductive model of CFRP

Table 1 shows the electric conductance of CFRP. For the aluminum plate, electric conductance of 5.96×10^7 [S/m] is used here.

Figure 8 is divided into 15,088,000 cubic cells (2050×160×46). Length of each side of the cell is 1 mm. Time step is 0.001668 [ns] here.